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Abstract

Liu et al proposed a method for combined embedded elements and cohesive zone (EE-CZ) modelling, which couples nodes on the outer surface of cohesive elements with matrix nodes. The effect of volume redundancy (presence of the matrix elements in the space occupied by the fibres) was reduced by subtracting the matrix stiffness from the stiffness of the embedded material (fibres or impregnated yarns). This method works only until de-bonding takes place (stiffness of the cohesive elements fully degrades to zero) as even after that the underlying matrix elements continue resisting the deformation. The main interfacial damage considered by Liu et al was the shear de-bonding caused by the fibre pull-out in the unit cell with low fibre volume fraction, in which case the spurious matrix resistance does not influence the results. In some other loading cases, for example, the material with high fibre volume fraction under the transverse loading. In the present letter the authors complement the EE-CZ approach, proposing a general method to handle the volume redundancy in EE-CZ modelling after de-bonding.

Keywords embedded element technique; cohesive element; interfacial damage; composites.

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Prof Antonio Ferreira,
Editor, *Composite Structures*

05.06.2019
Leuven

Dear Prof Ferreira,

following our brief e-mail exchange, I submit, on behalf of the co-authors, for publication in *Composite Structures* a Letter to Editor

Reduction of the volume redundancy in combined embedded elements/cohesive zone modelling – Comments on the paper: Liu Q, Gorbatiikh L, Lomov SV. A combined use of embedded and cohesive elements to model damage development in fibrous composites, Composite Structures, 2019, , 223:110921 (doi 10.1016/j.compstruct.2019.110921)

In this Letter we propose and validate a method for handling volume redundancy in combination of embedded elements and cohesive zones (EE+CZ), proposed in paper by Liu et al. This fills a gap which was not covered in this original publication and allows using the EE+CZ method with confidence.

I confirm that all the co-authors agree with the submission and that the Letter is not published or submitted for publication in another journal.

Yours sincerely

Stepan Lomov

Reduction of the volume redundancy in combined embedded elements/cohesive zone modelling – Comments on the paper: Liu Q, Gorbatikh L, Lomov SV. A combined use of embedded and cohesive elements to model damage development in fibrous composites, *Composite Structures*, 2019, 223:110921 (doi 10.1016/j.compstruct.2019.110921)

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Liu et al [1, 2] proposed a method for combined embedded elements and cohesive zone (EE-CZ) modelling, which couples nodes on the outer surface of cohesive elements with matrix nodes. The effect of volume redundancy (presence of the matrix elements in the space occupied by the fibres) was reduced by subtracting the matrix stiffness from the stiffness of the embedded material (fibres or impregnated yarns) [3, 4]. This method works only until de-bonding takes place (stiffness of the cohesive elements fully degrades to zero) as even after that the underlying matrix elements continue resisting the deformation. The main interfacial damage considered in [1] was the shear de-bonding caused by the fibre pull-out in the unit cell with low fibre volume fraction, in which case the spurious matrix resistance does not influence the results. In some other loading cases, for example, the material with high fibre volume fraction under the transverse loading. In the present letter the authors complement the method of [1], investigating a general method to handle the volume redundancy in EE-CZ modelling after de-bonding.

Except for the fibre stiffness reduction, there is another common way to deal with the volume redundancy in EE modelling: disregarding the shape functions in the overlapping regions in the

matrix, so the stiffness of the matrix under embedded regions equals zero [5]. This method is used here as the starting point; in the commercial finite elements code ABAQUS a user-defined field subroutine (USDFLD) is defined to select integration points of the matrix elements underneath the embedded regions. The stiffness in these specific integration points is reduced to a low value through user-defined material subroutine (UMAT).

The geometric boundary of matrix elements whose integration points are located in the range of embedded regions has a non-straight polygonal shape, as the host and the embedded meshes are independent. There is also a sudden change of stiffness at the boundary. These two reasons generate spurious peaks in the stress field near the boundary. To take away these non-physical phenomena, a transition region in the matrix is created with a width equal to half of the matrix element length (Fig.1a). A fixed value is set as the stiffness of transition region. This value depends on the material properties, which equals 10% of the matrix stiffness in this work.

Two unit cell models of unidirectional fibre reinforced composite with regular and random packing are considered to verify the proposed method (Fig. 1b, c). The results of EE-CZ modelling are compared to that of continuous mesh (direct) method. Both of the unit cells have fibre volume fraction of 38.5% and they are loaded with transverse tension in X direction. The thickness of the both models in Z direction is $0.04 \cdot D_f$, where D_f is the fibre diameter. Fibres and matrix are meshed with 8-node linear and reduced integration (C3D8R) elements, and interfaces between them are simulated using 8-node cohesive (COH3D8) elements. The element size of different parts is $0.04 \cdot D_f$, cohesive elements have a $0.01 \cdot D_f$ thickness.

For the regular model (Fig. 1b) a uniform X-displacement is specified on X-faces, normal displacements on other faces are zero, other displacement components are free; for the random

model (Fig. 1c) periodic boundary conditions are applied, with a prescribed X direction deformation and all other deformation components equal to zero.

In the material coordinate system (CS) 123 for fibres, as shown in Fig 1, 1-direction (fibre direction) corresponds to the global Z axis, 2- and 3- directions (transverse directions) correspond to global X and Y axis separately. Elastic material properties are used for fibre simulation: $E_1 = 230$ GPa, $E_2 = E_3 = 15$ GPa, $\nu_{12} = \nu_{13} = 0.20$, $\nu_{23} = 0.35$, $G_{12} = G_{13} = 22$ GPa, $G_{23} = 5.55$ GPa, where E_i , G_{ij} , and ν_{ij} denote tensile modulus, shear modulus and Poisson's ratio. Melro's damage model for matrix [6] is used, with the Young's modulus E set to 3.76GPa, the elastic and plastic Poisson's ratio ν and ν_p set to 0.39 and 0.3 respectively, tensile and compressive strength X_t and X_c set to 93MPa and 124MPa respectively, and fracture energy G_f of the matrix set to 0.09 N/mm. The stiffness, three nominal stress thresholds and fracture energy used for numerical analysis of cohesive zone are set to 10^6 MPa/mm, 40 MPa, 60 MPa, 60 MPa and 0.05 N/mm respectively.

Fig.2 shows the comparisons of numerical results between direct and EE-CZ modelling for the regular and the random models.

Figures 2a, b present stress-strain diagrams. Fig. 2a presents two volume redundancy elimination methods: the fibre stiffness reduction and zeroing the matrix stiffness under the fibre, as described above. The former method corresponds well with the direct model before the initiation of de-bonding, but results are wrong after de-bonding takes place. The discussion below is based on the latter method. In both Fig. 2a and Fig. 2b, the stress-strain curve has two characteristic points A and B: (a) A denotes the onset of the interfacial de-bonding; (b) B corresponds to the matrix damage onset. Up to point B, the correspondence between the stress-strain curves predicted by the direct

and EE-CZ models is almost perfect. EE-CZ model underestimates the matrix damage onset strain and the ultimate strain of the composite. This is caused by local spurious stress concentrations in EE-CZ model, not fully eliminated by the transition region.

Figures 2c, d show the predictions of de-bonding propagation. Fig. 2d shows two fibres (#1 and #2 in Fig. 1c). The predictions of the direct and EE-CZ models agree well, both in the de-bonding initiation and its progression.

Figures 2e, f show the normal stress in cohesive elements before and after de-bonding (0.6% and 2% applied strain for the regular model, Fig 2e, and 0.57% and 0.7% for the fibre #1 in the random model, Fig. 2f). An overall observation is that the interfacial stress profiles in direct and EE-CZ methods correspond well, although EE-CZ stress profiles fluctuate around the values obtained in the direct modelling. This fluctuation is mainly caused by the fact that the cohesive elements are embedded into a matrix region with a zigzag boundary. These fluctuations are quite pronounced at the ends of the de-bonded zone in fibre #1 of the random model (Fig. 2f). The fluctuations can lead to a difference between the exact position of the de-bonding and matrix damage zone in the multi-fibre model. Fig. 2h shows the damage configuration in the direct and EE-CZ models at the applied strain 0.7%. The differences, albeit less pronounced, are observed also for the regular model (Fig. 2g).

To conclude, this work advances the volume redundancy elimination strategy in the EE-CZ method, proposed in [1, 2]. The modified method can be applied to situations, when the volume redundancy plays a significant role, e.g. for modelling fibre reinforced composites with high fibre volume fraction. The results compare well with the direct modelling in overall stress-strain behaviour and the de-bonding initiation and development, and produce local surface stress

fluctuations, typical for the embedded elements methods.

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Figure 1. Schematics of the matrix regions (a) and models and meshes used for the method validation: regular (b) and random (c) fibre packing

Figure 2. Comparisons of direct and EE-CZ simulations in the regular (left) and random (right) models: stress-strain diagrams (a and b); development of interfacial crack angle (c and d, only fibre #1 and #2 are compared in d); interfacial stress before and after debonding (e and f, fibre #1 is shown in f as an example); damage in cohesive zone and matrix, applied strain of 2% (g) and 0.7% (h).